STATUS OF RESEARCH AT STANFORD UNIVERSITY ON SUPERCONDUCTING ELECTRON LINACS*

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(Presented by P. B. WILSON)

1. INTRODUCTION

Present electron and proton linear accelerators are limited in their capabilities as tools for nuclear research by low duty cycle. In order to overcome this limitation, investigators at several laboratories have considered the possibility of making the RF structure of a linac superconducting. Banford and Stafford [1] at Harwell proposed the feasibility of a superconducting proton linac in 1961, and have carried out experimental measurements on lead and niobium at 400 mc using quarter-wavelength hairpin resonators. In the same year measurements were started by Susini [2] and others at CERN and the University of Lausanne on lead and niobium surfaces at 300 mc using a capacitively-loaded coaxial resonator. Recently Montague [3] has considered the feasibility of a superconducting RF separator which can match the inherent high duty cycle of the CERN proton synchrotron.

Also in 1961, a program was started at Stanford University to measure the properties of superconductors in a microwave cavity at 2856 mc. The principle purpose of the investigation has been to determine the feasibility of superconducting electron linacs with high duty cycle. The initial apparatus, method of measurement, and early experimental results have been described elsewhere [4]. In this paper more recent results obtained from the RF cavity measurements will be presented.

In addition to the RF cavity measurements, calculations have been carried out concerning the design of superconducting electron linacs, taking into account beam loading, de-tuning and mis-phasing. In this paper simplified relations for the case of in-phase and on-resonance operation, together with the experimental results from the cavity measurements, will be used to discuss the design of possible high energy, high duty cycle, superconducting electron linacs.

2. RF CAVITY MEASUREMENTS

Fig. 1 shows the cryostat and cavity used in the measurements to date. The cavity is about 14 cm in diameter by 14 cm in length and is resonant at 2856 mc in the TE_{011} mode. In this mode there is no current flow across the joints between cavity side wall and end-plates, so that the Q is independent of the contact at these joints. Another important feature is a variable coupling loop at «N», wich allows the RF coupling to the cavity to be varied as needed during operation. Note also that the cavity is fastened by one end-plate to the helium reservoir, and that rather long thermal conduction path is present between the helium reservoir and the lower end-plate.

The Q of the cavity is measured by the decrement method. RF power incident on the cavity is modulated on and off in time. The loaded Q is obtained by measuring the time constant for the decay of the radiated power emitted from the cavity after the incident power has been switched off. The unloaded Q is obtained using the relation $Q_u=(1+\beta)Q_L$, where the coupling coefficient β is obtained by observing the detailed shape of the reflected power waveform (see Ref. [4]).

Measurements have been made on several types of tin and lead surfaces. Electroplated surfaces have given the highest Q's. Our early results on cavity Q as a function of temperature for electroplated tin and lead are shown in Fig. 2. The points are experimental values while the curves are plots of the relation in the upper

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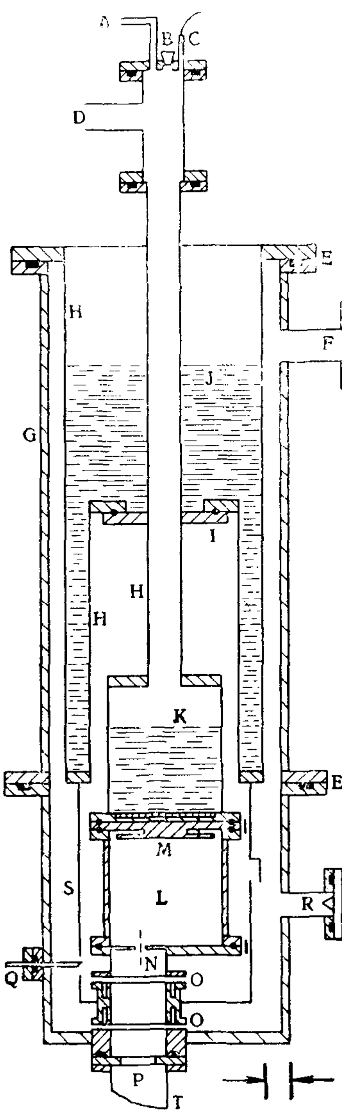

Fig. 1. Cryostat for superconducting RF cavity measurements:

A — to manometer; *B* — helium transfer port; *C* — lead in wires for resistor level gauge; *D* — to pump and pressure regulator; *E* — rubber 0-ring gasket; *F* — to diffusion pump; *G* — aluminum outer wall; *H* — stainless steel tubing; *I* — indium gasket; *J* — liquid nitrogen reservoir; *K* — liquid helium reservoir; *L* — RF cavity; *M* — end plate with mode trap; *N* — variable coupling loop; *O* — choke joint; *P* — RF window; *Q* — coupling adjustment; *R* — ion gauge; *S* — copper heat shield; *T* — input waveguide.

right corner of the figure. The constant 780 is a geometrical constant for our particular cavity relating cavity Q to surface resistivity. The denominator is Pippard's empirical relation for the high frequency surface resistivity of a superconductor, where the constant A (ω) has been obtained from the data of other investigators, and where R_0 is a residual resistivity at 0°K.

The resistivity of a perfect superconducting surface should vanish as temperature approaches zero for frequencies f such that $hf < 3.5\ kT_c$. Experimentally, a residual resistivity R_0 is always observed as T approaches zero. It has

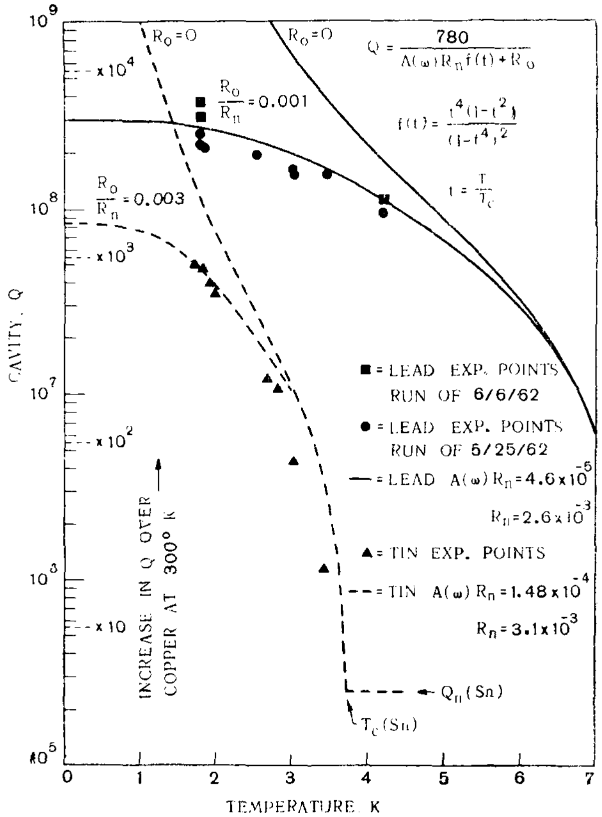

Fig. 2. Early experimental results on Q of superconducting microwave cavity.

previously been assumed that this residual resistivity is an inherent property of the particular surface, due to strains, roughness, impurities, etc. However, some of our recent measurements indicate that at least part of this residual resistivity may be due to trapped magnetic flux. The maximum Q we can obtain at a given temperature has been found to depend on the strength of the dc magnetic field in which the cavity was cooled. At 2° K the maximum cavity Q as a function of dc magnetic field is shown in Table 1.

A second piece of evidence supporting the trapped flux theory is the fact that these maximum Q's are obtained only after the application and then removal of high RF power into the cavity. This «training» effect increases the Q by about a factor of 2 over the Q measured before the application of high power. Apparently the application of high strength RF fields

Table 1

Maximum Q of Lead Cavity as a Function of dc Magnetic Field

Magnetic Field	Cavity Q
5 Gs	200×10^6
0.5	500
0.05	700

causes a re-distribution of the regions of trapped flux, either by pushing them into areas of low field strength in a cavity corners, or by combining a large number of regions of trapped flux into a smaller number with the same total area but less total boundary length. We have recently constructed a new cryostat which is magnetically shielded to about one milligauss in order to investigate this effect further.

The question of cavity behaviour at high power levels is crucial if superconducting accelerators and RF particle separators are to be feasible. The maximum RF magnetic field strength in our cavity occurs at the midpoint of the cylindrical side wall. The RF magnetic field approaches a limiting value of about 150 Gs as the incident power coupled into the cavity is increased. However, recent measurements indicate that this saturation effect may not be fundamental, but due simply to the fact that portions of the cavity are heating up at high input power. Carbon resistance thermometers placed in contact with the cavity during a recent run indicate that a significant temperature rise takes place at high input power levels. This is not unreasonable, since as is seen from Fig. 1, the cavity is cooled from one end. The thermal impedance of the heat path through the side walls of the copper cavity, and the unknown impedance of the jôints with indium gaskets, can easily explain the temperature rise.

In order to resolve this question, a new cryostat has been built in which the cavity is entirely immersed in the liquid helium bath. The construction of the cryostat is shown in Fig. 3. Also shown at «*L*» is the magnetic shielding for the experiments mentioned previously at very low field strengths. At the time of writing of this paper, measurements have not yet been made with the new apparatus, but are expected to begin soon.

Several interchangeable end-plates have been made for the new cavity so that various materials and methods of coating or plating can be given a rapid preliminary check. Niobium endplates will be tested in the near future.

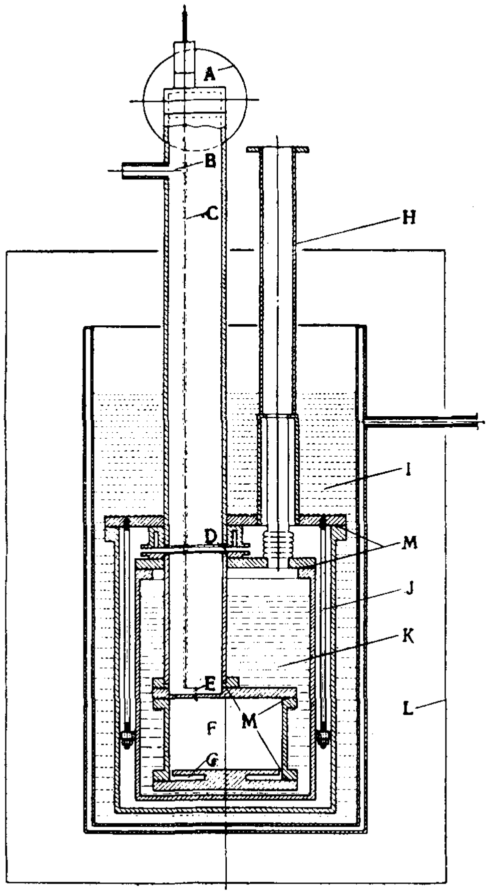

Fig. 3. Redesigned cryostat for superconducting cavity measurements:

A — input waveguide and vacuum window; *B* — vacuum pump-out; *C* — control rod for cavity coupling loop; *D* — RF choke joint; *E* — variable coupling loop; *F* — RF cavity; *G* — mode trap; *H* — helium pumping line; *I* — liquid nitrogen; *J* — support rods for helium resevoir; *K* — liquid helium; *L* — magnetic shielding; *M* — indium gaskets.

3. DESIGN EQUATIONS FOR SUPERCONDUCTING ELECTRON LINACS

A resonant cavity can be formed by placing conducting planes an integral number of halfwavelengths apart at appropriate planes of symmetry in the usual RF structure suitable for travelling-wave electron linacs. If now this cavity is made superconducting and a small coupling loop is added to couple in RF power, a small amount of input power will create a very high electric field strength on the axis of the structure. If cylindrical drift tunnels below cut-off are added at each end so that an electron beam can enter and leave, the result is a section of standing-wave electron linac. The design equations for an accelerator of this type are given in Table 2.

Table 2

Superconducting Accelerator Design Equations

$$V=\sqrt{\frac{1}{2}P_W L r_{300}(Q/Q_{300})} \quad (1)$$

$$P_R\approx\left(\frac{300^\circ}{T}\right)\left(\frac{1}{\eta R}\right)P_W \quad (2)$$

$$C_R\approx\$6{,}000\,(P_W)^{0.6} \quad (3)$$

$$P_B=P_O-P_W \quad (4)$$

$$\beta=P_O/P_W \quad (5)$$

$$i_B=P_O/V \quad (6)$$

$$Q_L=\frac{Q_0}{1+\beta}\approx\frac{(Q/Q_{300})\times10^4}{\beta}\ \text{at 3 kmc} \quad (7)$$

$$H_{RF}\ (\text{in gauss})\approx0.004\ V/L\ (\text{in volts/cm}) \quad (8)$$

$$Q/Q_{300}\sim f^{-3/2} \quad (9)$$

$$r_{300}\sim f^{1/2}$$

$$r_{300}\,(Q/Q_{300})\sim f^{-1}$$

The first equation gives the energy gain in terms of the power P_W dissipated in the walls of the structure. The length of the structure is L, the shunt impedance per unit length of a copper structure at room temperature is r_{300}, and the improvement factor in Q over the Q of a copper structure at room temperature is Q/Q_{300}. This last quantity is measured experimentally to be 2,500 for an electroplated lead surface at 4.2° K at low power levels. The second equation gives the input power into a refrigerator operating at T° K which is necessary to remove the power P_W being dissipated in the RF structure. The first factor is the approximate Carnot efficiency, while the second factor involves the efficiency η_R of a practical refrigerator with respect to the Carnot efficiency. Current refrigerators operating at 4.2° K have efficiencies $\eta_R\approx7\%$, but refrigerator experts feel that $\eta_R=15\%$ is not unreasonable for large installations in the future. The third relation gives the estimated cost of large refrigerators, based on prices obtained from several companies. The fourth equation states that the beam power is equal to the total RF input power P_0 less dissipated power P_W. This assumes that the cavity coupling is adjusted properly for the cavity Q and beam current, so that there is no reflected power from the cavity. The proper value of the coupling coefficient is given by (5), and the beam current by (6). The loaded Q of the structure is given by (7), based on the fact that $Q_{300}\approx10^4$ at 3 kmc. Relation (8) gives the approximate peak RF magnetic field strength at the wall of a resonant section of typical disk-loaded structure in terms of the energy gain per unit length on the axis. At 4.2° K the critical dc magnetic field for lead is a little over 500 Gs, while that for niobium is about 1400 Gs. However, it is not yet known whether the high-frequency RF magnetic field is limited to the value of the dc critical field. Finally, relations [9] show how r_{300} and (Q/Q_{300}) vary as a function of frequency f. The relations are valid in the region below about 3 kmc.

4. DESIGN OF TWO HIGH ENERGY SUPERCONDUCTING LINACS

Table 3 shows application of the preceeding relations to the design of a 1 GeV and a 20 GeV accelerator with 10% duty cycle. Here N is the total number of klystrons, each having an output power $P_K=P_0/N$.

Table 3

Two Representative High Energy Superconducting Accelerators

A. 1 GeV—10% duty cycle	B. 20 GeV—10% duty cycle
$T=4.2^\circ$ K	The same as *A* except:
$Q/Q_{300}=2{,}500$	
$r_{300}=5\times10^5\ \Omega$/cm	
$L=150$ m	$L=3{,}000$ m
$P_W=10$ kW (ave)	$P_W=200$ kW (ave)
$P_R=5$ MW ($\eta_R=15\%$)	$P_R=100$ MW
$C_R\approx\$1{,}500{,}000$	$C_R\approx\$10{,}000{,}000$
$N=10$	$N=200$
$P_K=10$ kW (ave)	
$P_0=100$ kW (ave)	$P_0=2$ MW (ave)
$P_B=90$ kW (ave)	$P_B=1.8$ MW (ave)
$i_B=90\ \mu$A (ave)	
$\beta=10$	
$Q_L\approx3\times10^6$	
$H_{rf}=260$ Gs	

Accelerators having the same energy, length, and duty cycle could be built using conventional design methods. However, the total average input power to the klystrons for the two machines would then be 50 MW and 1,000 MW. It is seen that by using a superconducting design the total input power has been reduced by an order of magnitude, and in addition most of the input power now goes into a large refrigerator rather than into high power klystrons.

The accelerators shown in Table 3 are based on the Q values we have actually obtained with lead at 4.2° K. However, machines of this type would be considerably more attractive if a factor of 10 reduction could be made in the required refrigeration power. There are several possible ways in which this might be accomplished. First, from relations (1) and (9) in Table 2, it is seen that P_W decreases linearly with frequency for a given energy and length. Although 3 kmc is a convenient frequency for RF cavity measurements, it appears that a lower frequency has several advantages for an accelerator. The refrigeration power should, for example, decrease by a factor of six in going to 500 mc. Also the larger hole size should decrease the possibility of beam interception, and in addition there is more surface area for heat transfer to the helium bath. Second, there is a possibility that at a given temperature niobium may give significantly higher Q's than we are now obtaining with lead. Third, it is possible in principle to recirculate the power in the structure by making the structure part of a resonant ring. This would decrease P_W by a factor of two. Fourth, by working at a lower temperature, a net decrease in refrigeration power is possible. Much depends on how close in practice the resistivity of an ideal surface can be approached at lower temperatures.

In summary it seems very possible that an order magnitude reduction in refrigeration power can be achieved. If this can be done, then the values of P_W, P_R, and C_R for machine A become 1 kW, 500 kW, and $ 400,000 respectively, while for machine B they are 20 kW, 10 MW, and by $ 2,500,000.

Under the assumption that refrigerator power is kept constant, energy and duty cycle can be traded. For example, by dropping to 6.3 GeV, machine B can be run cw with the same refrigerator, while by going to 40 GeV the duty cycle becomes 2.5% with $H_{RF}=500$ Gs. At 100 GeV the duty cycle drops to 0.4% while $H_{RF}=1400$ Gs (the dc critical field for niobium at 4.2° K).

5. CONCLUSION

Much work remains to be done before the feasibility of such accelerators is definitely established. We hope to resolve the question of the high-field behaviour of lead and niobium surfaces in the near future. In addition we are currently building a resonant section of disk-loaded S-band accelerator structure one foot in length with an electroplated lead surface. After checking the Q of the structure we plan to add an electron gun and test it as an actual accelerator. With the 1 kW klystron available, it chould be capable of delivering a 3 MeV cw beam at 200 μA.

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DISCUSSION

E. G. Komar

1. Does the value of the electric field strength in the resonator vacuum spaces vary at low temperatures near absolute zero?

2. What method for depositing niobium do you propose to use—electrolytic or some other method?

P. B. Wilson

1. I do not know. Measurements made at liquid nitrogen temperature show only a small improvement in the electric field strength for electrical breakdown in vacuum.

2. A method of niobium ploting has been developed by the Linde Co. in the USA. Niobium is ploted from on electrolyte which is composed of molten solts at about 700° C. I do not know the details.

R. Wideröe

1. Have you considered the problem of beam loading on the cavities?

2. Would it not be better to have a 100% duty cycle?

P. B. Wilson

1. Yes. We have made calculations which take into account beam loading, de-tuning, and out-of-phase operation of the cavity.

2. A duty cycle of 100% is certainly desirable, and the highest energy at which this can be achieved depends on the amount of refrigeration power that one is willing to pay for. It may still be desirable to go to still higher energies at less than 100% duty cycle.

E. S. Borovik

1. A maximum field of H = 150 Gs is attained. What was the critical field under these conditions?

2. In order to estimate the required power for cooling, only the usual resonator losses were considered; the energy inherent in the beam is very great and small beam losses may lead to a sharp increase in the required cooling power.

P. B. Wilson

1. About 700 Gs.

2. The beam must be focused properly. I think this problem is not very essential.

R. Wideröe

1. I would like to mention that beam loading seems to be a very serious problem. The beam has to be accelerated and for this we need RF-Power. This power must be switched on exactly proportional to the beam in the cavity. In Harwell (Rutherford Labs) they have proposed normaly to dump the RF-Power in a resistor parallel to the cavity (spoiling the Q-value) and switch the resistor out when the beam current starts.

2. Due to the high Q-value of the cavities they will need a relative long time to reach the high fields and consequently a 100% duty cycle (which is also wanted for many experiments) will be necessary.

P. B. Wilson

1. In the case of a superconducting microwave cavity, most of the RF power is reflected back to the source (klystron) when the beam is off. This can be taken care of by a high power isolator.

2. The filling time for the superconducting cavity is of the order of milliseconds. The duty cycle can be less than 100% as long as the pulse length is long compared to the filling time, perhaps 100 milliseconds.

A. I. Didenko

I have an addition to Prof. Wideröe's question. What was the basis for the author's assurance that the beam load would not essentially affect such accelerators? If the length of the section is compared to the attenuation length, the beam will lead to a reduction in the field along the section where, for the focused current, this effect increases with an increase in system quality.

Chairman

I propose that Dr. Didenko study this question in a special discussion with Dr. Wilson.